Experiences in the grinding of silicon nitride on a lower cost high speed CNC grinder

by

Tae Wook Hwang[1,2], Eric P. Whitenton[2] and Chris J. Evans[2]

1. Department of Mechanical & Industrial Engineering,
University of Massachusetts, Amherst, MA 01003

2. National Institute of Standards and Technology,
Precision Engineering Division,
Gaithersburg, MD 20899, USA

Abstract:

An investigation into high speed grinding of ceramics has been conducted to understand machine dynamics, wheel wear, and ground surface morphology. Some preliminary results are reported for modal testing and wheel wear together with microscopic observations of the ground surfaces. The modal testing of a 4-axis computer numerical control (CNC) grinder reveals a vertical vibration of the wheel acting as a local "jack-hammer". As the wheel speed increases above 10000 rpm, the spindle and the motor cause vibrations. Wheel wear test using a single-layer plated diamond wheel for grinding of silicon nitride shows that the grinding ratio (*G*-ratio) is a nearly constant 840 mm^3/mm^3, and surface roughness (R_a) of the ground specimen decreased from 1.6 μm at the beginning to 0.4 μm at the end of wheel life. Measured normal force per unit width was found to increase reaching 200 N/mm at near the end of wheel life starting from about 10 N/mm at the beginning. This is primarily due to the development of wear flat areas on the active cutting points. Much remains to be done to separate the various affects alluded to in the high speed grinding of ceramics.

Keywords: high speed grinding, ceramics, plated diamond wheel, wheel wear

I. Introduction

Silicon nitride is the material of choice for a broad range of applications – including cam followers, hybrid bearings, pump seals, and blades in high temperature stationary turbo-generator sets. One primary limitation to the introduction of these materials is the cost of machining parts with adequate form, finish, and strength using "conventional" grinding processes [1]. One approach to obtaining complex contours in conventional grinding is to dress the inverse of the required feature into a grinding wheel. Such a process is typically expensive, and non-uniform wheel wear tends to cause loss of profile accuracy.

Over the last decade, a great deal of work has been done investigating the use of single layer plated cubic boron nitride (CBN) wheels for form grinding of hard steels and superalloys. Such wheels are particularly well suited for high speed operation and, provided wheel wear is reasonable, can be used to economic advantage.

This paper is a preliminary report of our investigations into the use of plated diamond wheels operating at high surface speeds in the grinding of silicon nitride. The experimental work is being performed on a lower cost, commercially available, high speed 4-axis CNC grinder.

II. Motivation

Breaking strength of ceramic components may be limited either by the inherent strength of the material or by flaws induced by the machining process. "Ductile regime" grinding is alleged to produce fracture-free surfaces while "low damage microgrinding" produces surfaces where fine scale fractures do not propagate deep into the work material. In indentation of isotropic homogeneous materials, a clear transition between "ductile" and "brittle" behavior occurs as a function of penetration depth. Transitions from "ductile" to "brittle" have been observed in grinding a range of brittle materials as a function of uncut chip thickness. Although the system behavior is obviously more complicated than is suggested by this simplified model, there appears to be a transitional range, where a mixture of plastic deformation and fine scale fracture takes place.

In peripheral wheel grinding, uncut chip thickness is a function of wheel diameter, depth of cut, feed rate (i.e. ratio of wheel speed to table surface speed), and grit spacing. For a given wheel speed and diameter (limits imposed in conventional ceramics grinding practice), the user can decrease uncut chip thickness by:

- Decreasing table speed or nominal depth of cut, both of which reduce stock removal rate linearly; or
- Decreasing grit spacing.

In practice, the grit spacing in conventional resin or metal bond grinding wheels may be decreased, to a limited extent, by increasing "concentration" or by decreasing the grit size. The latter strategy also decreases the "chip clearance", or volume available to remove the swarf since the individual grains typically require about half the grain to be "held" in the bond. This, practically, limits the achievable depth of cut.

There have been a number of advances in high speed grinding of super-alloys using plated CBN wheels. Wheel surface speeds now approach 200 m/s in industrial practice, with speeds up to 500 m/s reported in research institutions. For ceramics grinding, it has been suggested that increased surface speed leads to increased ductility through adiabatic heating and hence to increased strength in the product. High spindle speed, however, may lead to increased vibration with the individual grits acting as indenters at the frequencies and amplitudes given by the dynamic performance of the machine.

Plated wheels allow much higher abrasive packing densities than can be achieved in conventional metal or resin bond systems and the single abrasive layers allow for much larger grit exposure. Hence, for a given wheel diameter and grain size, a plated wheel should give smaller uncut chip thickness and higher ground part strength than would be obtained with a conventional wheel. Unlike conventional wheel bond systems, a plated wheel cannot be dressed or self-dressing; the single layer of abrasives is bonded directly to the wheel core. Wheel life is given directly by grit wear rates; economic application of such wheels depends, therefore, on grit wear rates.

Machining induced fracture depends, in large measure, on the extreme value of grit penetration, rather than the mean. The height distribution of grits on an as-plated wheel depends on the grain size distribution; its effect, however, may be mitigated in one of two ways;

- Using a “dresser” to mechanically pluck the high grits from the bond; or
- Grinding a sample which will chemically dress the high grits; for diamond wheels, good candidates are chrome and tungsten.

The National Institute of Standards and Technology (NIST) program in high speed grinding of ceramics is attempting to separate the various affects using an Edgetek 4-axis CNC grinder* (see Figure 1). Work is also underway to understand the machine characteristics and their impact of grinding performance.

III. Machine dynamics

There is no point selecting process parameters which give small undeformed chip thickness if the machine dynamics result in the wheel acting as a local “jack-hammer”. From the perspective of the dynamics, there are two primary sources of relative motion between the work and the wheel: driven headstock vibrations, which are typically a function of spindle speed, and the lowest vibration modes of the machine structure.

III-1. Modal testing

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* Specific commercial products are identified solely to provide a complete description of the experimental work and does not imply an endorsement by National Institute of Standards and Technology, nor does it imply that they are necessarily the best for the purpose.

One important consideration in high speed grinding of ceramics is to reduce the undesirable vibrations which can potentially cause strength degradation of the workpiece. A slightly unbalanced wheel at high spindle speed exerts high enough in-process impact energy on the workpiece to reduce the strength, although moderate process parameters are applied during grinding. In this section, the dynamic response of an Edgetek grinder will be discussed from a various aspects including the effects of wheel balance, wheel mass, and coolant. Dynamic measurements made in-process will also be discussed.

A 26 kW motor drives the spindle using v-groove belts and pulleys, and rotates about 2.5 times slower than the spindle. For the measurement of vibration, two accelerometers were mounted on the spindle housing placed at end of the spindle. One was sensitive primarily in the vertical direction while the other was primarily sensitive in the horizontal direction. During the test, the data collected was fed into a personal computer (PC) through a signal analyzer for further analysis as shown in Figure 2.

III-2. Results and discussion

Prior to in-process vibration testing, a hammer equipped with a load cell was vertically applied on the non-rotating spindle nose and frequency response function was obtained as shown in Figure 3. The result shows the presence of two dominant structural modes with the highest peak at about 400 Hz. Since the spindle is designed to be run from 8000 rpm (133 Hz) to 14000 rpm (233 Hz), one would expect that a spindle speed of around 11700 rpm, corresponding to a motor frequency of about 78 Hz, may be troublesome if the motor vibrates enough to stimulate the 78 Hz peak. Later in this paper, the issue of the motor vibration will be discussed further.

Vibration testing analysis was conducted with the spindle rotating over a wide range of wheel speeds for unbalanced and well balanced wheels, light and heavy wheels. Furthermore the effect of coolant on the frequency response of the grinding machine was investigated. The results are presented in Figures 4 - 5. The top row of graphs are the total integrated displacement as a function of the spindle speed. The bottom row of graphs are the frequency at the maximum displacement amplitude as a function of spindle speed, showing which frequency is the primary contributor to the overall displacement. The label ‘S’ in lower figures denotes the frequency at the peak displacement where the spindle frequency corresponds to this frequency. Label ‘M’ the peak frequency, corresponds to the motor frequency, and the label N, the noise floor of the accelerometers and those frequencies that are not a harmonic of motor and spindle. The vertical displacements as shown in these figures for the balanced wheel exhibit much larger amplitude compared to the horizontal ones as the spindle speed increases above 10000 rpm. For the unbalanced and balanced wheels shown in Figure 4, the dominant mode of machine vibration changes from spindle frequency to motor frequency or both as the wheel balance is improved. Therefore it would be expected that the motor causes undesirable vibrations as the spindle speed increases above 10000 rpm even with a well balanced wheel.

Next the mass of the wheel was increased by approximately 50 %. Comparing the left column of Figure 5 with the right column of Figure 4 shows that, with this mass increase, what seemed to be one vertical displacement peak is actually two peaks which separate and move apart. Mass changes give us the ability to move the peaks around to improve machine performance. If we are operating at 12000 rpm, we want a heavier wheel. If we are operating at 11000 rpm or 14000 rpm, we want a lighter wheel. The right column of Figure 5 shows how the coolant has the effect of somewhat dampening the motor vibrations in the vertical direction. The two peaks become lower and just slightly broader when the coolant is applied.

Up to now, the dominant mode of machine vibration under the various conditions is at the frequencies originating from either the spindle or the motor, or both. Similar vibration modes can be seen in Figure 6 obtained during grinding of slipcast sintered silicon nitride with a depth of cut 25 μm and wheel speed 110 m/s (10300 rpm). From the frequency response function as shown in this figure, both the spindle and the motor frequencies exist together, contributing comparably to the overall displacement. However another set of experiments with more aggressive process conditions shows that the overall displacement is dependent on the spindle frequency. This indicates that wheel out of roundness and other synchronous sources of variation modulate the grinding forces at the spindle frequency, resulting high impact forces on the workpiece.

The modal testing suggests that two sources, the spindle and the motor, mainly contribute the vibration of the machine during the process. An attempt was made to reduce the motor vibration of a well balanced wheel. For this purpose, weights were clamped to the rotor at the motor's free standing end to perform a single plane balance. Then a spindle speed of 14000 rpm was selected and weights were adjusted to obtain the minimum vibration at the given spindle speed. Once the balancing was achieved, the spindle speed was increased in increments of 200 rpm from the lowest 8000 rpm up to 14000 rpm. The measured maximum displacement was plotted versus corresponding spindle speed in Figure 7. As can be seen from the results, the displacement steeply reaches a maximum at about 11700 rpm and decreases as the spindle speed increases. Since the motor frequency corresponding to the spindle speed of 11700 rpm is 78 Hz, the main source at this condition is likely to be one of the machine's structural modes which we found from the hammer test (see Figure 3). Similar behavior was also found for the spindle speed of 13000 rpm as shown in Figure 7. It is clear that there is no one "correct" balance which is optimal at all speeds. This suggests that motor balancing must be adjusted as a function of the spindle speed. To address this, a simple "proof of concept" experiment was performed. An electromagnetic voice coil shaker was mounted in the free end of the motor in the vertical direction as shown in Figure 8. The same frequency as that of the motor was applied to the shaker with a 180^{o} phase shift to eliminate the vibration from the motor. We found the shaker effectively reduced the motor vibration.

IV. Wheel wear and effect on ground surface topography

A wheel wear test was conducted using a 180 grit size electroplated diamond wheel. The results show that, after an initial transient region, the grinding ratio (*G*-ratio) is nearly constant at 840 mm^3/mm^3. Surface roughness (R_a) of ground specimens decreased from 1.6 μm at the beginning to 0.4 μm at near the end of wheel life. However measured normal grinding force was found to increase reaching about 200 N/mm starting from about 10 N/mm.

Surface profiles of ground specimens collected at various stages of grinding times were analyzed using both areal power spectrum density(APSD) and areal autocorrelation function(AACF) together with microscopic observations with scanning electron microscopy (SEM). The APSD reveals a concentrated energy distribution across the grinding direction and the relative energy decrease with smoother ground surface. The AACF exhibits strong correlation along the grinding direction and steeply decays across the grinding direction.

IV-1. Experimental works

Straight surface grinding experiments were conducted under plunge conditions (no crossfeed) in the down mode on a Edgetek 4-axis CNC machine equipped with a FANUC 16M* controller. One grinding condition was selected for the wear test: depth of cut a = 50.8 µm, workpiece velocity v_w = 63.5 mm/s, and wheel velocity v_s = 85 m/s. During grinding, a copious coolant flow was applied with additional coolant directly on the wheel surface to remove swarf. Measurements were made of the grinding power using a power meter, the grinding force components using a piezoelectric dynamometer (Kistler 9257A*), and spindle vibrations using accelerometers. The data acquisition system is illustrated in Figure 2.

The workpiece material was a slipcast sintered silicon nitride (AlliedSignal, AS800*). The mechanical properties at ambient temperature given by the manufacturer are fracture toughness K_c = 8.0 (MPa $m^{1/2}$), hardness H = 16 GPa, elastic modulus E = 310 GPa, and Poisson's ratio ν = 0.28. All workpiece specimens were machined to the same initial dimensions 21.6 mm x 12.7 mm x 50.8 mm. Grinding was in the longitudinal (50.8 mm) direction with wheel engagement across the entire width (12.7 mm).

The same 180 grit single layer nickel plated wheel (Abrasive Technology*) for the modal test was used of diameter d_s = 203.2 mm (8 inches) and width b = 25.4 mm (1 inch). The grit dimension measured using an optical microscope was about 90 µm, which is very close to the expected value of 85 µm estimated as 60 % of the mesh spacing. The cutting point density C for the wheel, obtained by counting grains on the wheel surface using an optical microscope, was $C \approx 67$ mm^{-2}, which is about three times bigger than what was found for a 100 concentration resin-bonded diamond wheel of the same grit size. This value of $C \approx 67$ mm^{-2} is about half the maximum grit density for areal packing in a rectangular array with a grit spacing equal to the 90 µm grit size.

For the measurement of wear depth on the wheel surface, a ceramic specimen with a smaller width than that of the wheel was first ground followed by grinding of a glass specimen of the same width as the grinding wheel. A surface stylus trace was then made both on the glass specimen to measure the wear depth and on the ceramic specimen to measure the surface roughness. For each specimen, three measurements were taken at different places and averaged. Four replicas were taken using acetyl cellulose tape at marked places around the wheel surface after completing each ceramic specimen. The replicated samples were examined using an optical microscope to see whether the topography of abrasive grains changes. Furthermore surface profiles of ground specimens were measured using a white light interferometer (WYKO Corporation, Rollscope*) to characterize the spatial properties related to the APSD and the AACF. 300 passes were taken on each ceramic specimen.

IV-2. Results

IV-2-1. Grinding force and wheel wear

During grinding, the normal force per unit width F'_n tended to progressively increase as shown in Figure 9. Initially F'_n was only about 10 N/mm, slowly increased up to about 25 N/mm after 500 s, and then increased at a much faster rate reaching 200 N/mm at end of the wheel life. After the wheel failure, pieces of plated layer were collected and observed using both SEM and optical microscopy. It is obvious from Figure 10 that wear flats on the active grains are developed and wear tracks along the grinding direction can be clearly seen in Figure 10(b). Therefore an increase of normal force is mainly due to an increase of wear flat area as grinding proceeded, which is consistent with the observations reported by others[2,3]. The measured grinding power (%) per unit width based on the maximum machine power of 26 kW in Figure 11 follows a similar trend as that of normal force. It should be noted that the transient effect due to the machine deflection causes the actual depth of cut to be less than the controlled infeed input to the machine when replacing a ground specimen with a new one.

The grinding test was terminated due to wheel failure while grinding the seventh ceramic specimen when the plated abrasive layer totally separated from the steel hub. The total volumetric material removal was 71,775 mm^3 corresponding to a volumetric removal per unit width of 5,652 mm^3/mm and a grinding time of 1752 s.

Surface profiles were measured after various amounts of grinding and the corresponding R_a values obtained are plotted versus grinding time in Figure 12. The surface finish progressively decreases with grinding time. The R_a value at end of the wheel life was found to be close to 0.4 μm, which is only about one fourth of the initial R_a value at the start of grinding. This improvement in surface finish does not necessarily guarantee less strength degradation of the workpiece because of the much bigger normal forces on the workpiece.

An attempt has also been made to obtain a better surface finish without causing such high grinding forces by “chemically” dressing a plated wheel with molybdenum [4]. Some preliminary results with a chemically dressed wheel (180 grit plated diamond) but otherwise identical grinding conditions as above indicate R_a value of about 0.5 μm with much lower normal force per unit width, less than 10 N/mm. A cross-plot of normal force per unit width versus surface roughness is shown in Figure 13. The chemically dressed wheel shows better performance than the as received wheel. Additional work is needed in this area.

Profilometry measurements on the ground glass specimen as shown in Figure 14 were used to obtain the wheel wear. The worn depth of the wheel (see Figure 14) appears to linearly increase after an initial transient region as shown in Figure 15 resulting into a similar trend on the plot of wheel wear per unit width versus volume of material removed per unit width in Figure 16. To characterize wheel-wear resistance, the grinding ratio (*G*-ratio), which is the volume of material removed (V_w) per unit volume of wheel wear (V_s), is computed as:

$$G = V_w / V_s \tag{1}$$

Results for both the instantaneous and accumulated *G*-ratios as estimated from Equation (1) are plotted versus grinding time in Figure 17. The accumulated *G*-ratio was calculated by dividing the total volume of workpiece removed by the total volume of wheel wear at a given time. These results suggest an instantaneous *G*-ratio of about 840 mm^3/mm^3 which is almost constant with grinding times except an initial transient region. No measurement was made during an initial grinding time. It is necessary to measure the wheel wear during the initial stage to find out the complete behavior of *G*-ratio over the wheel life. The accumulated *G*-ratio increases but is much smaller than the instantaneous steady state value due to the expected initial high run-in wear.

IV-2-2. Topography of ground surface

The ground ceramic specimens collected at various stages of wheel wear were observed using SEM. Surface profiles measured using a white light interferometer were analyzed to characterize three - dimensional (3D) topography.

The advantage of 3D surface analysis over two - dimensional (2D) analysis is 3D provides spatial properties which distinguish isotropy and anisotropy of engineered surfaces. In a 2D profile assessment, the autocorrelation function (ACF) and the power spectrum density (PSD) have been considered as a good candidate to characterize spatial properties of the profiles [5,6]. Similarly for 3D surfaces, the areal autocorrelation function (AACF) and the areal power spectrum density (APSD) have been widely used to characterize the spatial property [7-9]. Therefore both AACF and APSD are applied to characterize the ground surfaces in the present paper. The details were found elsewhere [9,10].

SEM photographs shown in Figures 18(a) - 20(a) were taken after the grinding time t = 264 s, 1048 s, and 1520 s, respectively. At the initial stage of wear as shown in Figure 18(a), the ground surface reveals deep characteristic scratches along the grinding direction which are mainly associated with extensive ductile flow. As the grinding continues and wheel wear increases, the ground surface becomes smoother with almost no presence of deep grooves as shown in Figure 19(a). Near the end of wheel life, the ground surface in Figure 20(a) reveals a somewhat different surface topography. A surface severely worn by rubbing/sliding would have a similar appearance. The corresponding surface profiles in Figures 18(b) - 20(b) show deep grooves along the grinding direction at initial stage of wear test and turn into smoother surface with grinding times.

The APSD for the ground surfaces in Figures 18(a) - 20(a) are presented in Figures 18(c) - 20(c) with a coordinate system where angular frequencies in two orthogonal axes are zero at the center of the figure and the maximum frequency is one half of sampled frequency. The APSD energy in Figures 19(c) and 20(c) are normalized with the maximum peak value of Figure 18(c). As expected, the APSD in all figures is concentrated across the grinding direction although relative energy concentration decreases with grinding times. The AACF are presented in Figures 18(d) - 20(d). A strong correlation is observed along the grinding direction and the AACF decay faster in the cross-grinding direction. As the ground surfaces become smoother with grinding times, the level of correlation along the grinding direction decreases and decay faster. The characteristics of the APSD and the AACF for the ground surfaces are similar to those of turned surfaces possessing the anisotropy along the cutting direction. To compare the spatial characteristics of an anisotropic surface to those of an isotropic one, the same ceramic specimen polished into the surface roughness (R_a) of 0.18 μm was also analyzed. The surface profiles together with the APSD and the AACF are presented in Figure 21 without normalization. The APSD energy for the polished surface in Figure 21(b) spreads out with much less directionality. For the AACF, it steeply decays in all direction representing a characteristic of an isotropic surface.

V. Conclusion

Cost-effective grinding of ceramics at high speed requires an understanding of machine dynamics and wheel performance while ensuring part quality. For this purpose, an investigation has been performed for the use of plated diamond wheel installed on a high speed 4-axis CNC grinder in the grinding of silicon nitride.

Modal testing showed the wheel acting as a local “jack-hammer” on the workpiece during grinding, which is mainly associated with the vibrations of the motor and the spindle as well as the lowest modes of machine structure. The vibration of the wheel during grinding was observed to steeply increase as the wheel speed increases above 10000 rpm. An electromagnetic voice coil shaker mounted in the free end of motor was found to effectively reduce the vibration originated from the motor at high spindle speed.

A wheel wear test using the 180 grit size single-layer plated diamond wheel showed that the grinding ratio (*G*-ratio) was nearly constant of about 840 mm^3/mm^3 after an initial transient region. Surface roughness (R_a) of ground specimen decreased from 1.6 μm at the beginning to 0.4 μm at near the end of wheel life. However the behavior of measured normal grinding force and energy were found to linearly increase as grinding times reaching the end of wheel life after an initial transient region. The measured normal force at near the end of the wheel failure was about 200 N/mm, which is about as twenty times bigger as the one measured at initial stage of wheel life. The development of wear flats on the active cutting points was found to be directly related to the increase of normal force. Surface topography of ground surfaces at a various stages of grinding times also showed quite different characteristics revealing a severely worn surface at near the end of wheel life, associated with rubbing/sliding, but a relatively smooth surface with less APSD energy and level of AACF.

References

1. Jahanmir S., Ives L. K., Ruff A. W., and Petersen M. B., 1992, "Ceramic Machining: Assessment of Current Practice and Research Needs in the United States," NIST Special Publication 834.

2. Malkin S. and Cook N. H., 1971, "The wear of grinding wheels, Part I-Attrious Wear," ASME J. of Eng. for Ind., pp.1120-1128.

3. Hahn R. C., and Lindsay R., 1967, "On the effects of real area contact and normal stress in grinding," Annals of the CIRP, Vol. 15, pp. 197-204.

4. Paul E., Evans C. J., Mangamelli A., McGlauflin M. L., and Polvani R. S., 1996, "Chemical aspects of tool wear in single point diamond turning," Precision Engineering, Vol. 18, pp. 4-19.

5. Whitehouse D. J., and Archard J. F., 1970, "The properties of random surfaces of significance in their contact," Proc. R. Soc. London, Ser. A, Vol. 316, pp. 97-121.

6. ANSI, Surface Texture: Surface Roughness, Waviness and Lay, American Standard ANSI B.46.1, 1985.

7. Longuet-Higgins M.S., 1957, "The statistical analysis of a random, moving surface," Philos. Trans. R. Soc. London, Ser. A, Vol. 249, pp.321-384.

8. Nayak, P. R., 1971, "Random process model of rough surfaces," J. Lubr. Technol. Trans. ASME, July, pp.398-407.

9. Dong W. P., Sullivan P. J., and Stout K. J., 1994, "Comprehensive study of parameters for characterizing three-dimensional surface topography, IV: Parameters for characterizing spatial and hybrid properties," Wear, Vol. 178, pp.45-60.

10. Bendat J. S., and Piersol A. G., Random data: analysis and measurements procedures, Wiley-Interscience, 1971.